

Intermediate depth earthquakes beneath the India-Tibet collision zone

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Abstract. We report on three intermediate depth earthquakes in the India-Tibet collision zone, two under the Himalayan Thrust Belt (HTB) and one beneath the Indus Zangbo suture. The m_b magnitudes of these three events are from 4.3 to 4.9, and are too small to be well located by conventional means. However, from modeling their broadband waveforms recorded at near-regional distances on a temporary PASSCAL array, we can confidently confine the sources to be below the crust, between 70 and 80 km deep. The existence of these intermediate depth earthquakes in this area suggests relatively low temperatures in the mantle lithosphere. The two events under the HTB display strike-slip mechanisms with some normal faulting component; this is quite different from the shallow thrust events typical of the same area. The principal P and T axes of all 3 fault plane solutions show roughly NS compression and EW extension, consistent with a regional stress field produced by the indenting of the India continent.

Introduction

Since the inception of the India-Eurasia collision at approximately 45Ma, the India plate has indented northwards about 2000 km, producing the highest continuous topography on earth, the Himalayas and the Tibetan plateau. In the past two decades, considerable efforts were made to investigate the crustal and upper-mantle structure of this area in order to understand the collision mechanism and formation of the plateau (see Molnar, 1988 for a review).

Among various approaches, studying the source characteristics and depth distribution of earthquakes provides unique information about the mechanical properties and stress orientation of the lithosphere. There have been numerous results published based on the relocation and the source inversion of large events in the Tibetan Plateau and surrounding areas (Molnar and Chen, 1983; Baranowski et al., 1984; Ni and Barazangi, 1984; Molnar and Lyon-Caen, 1989; Zhao and Helmberger, 1991). These studies conclude that seismicity beneath the Tibetan plateau is shallow, restricted to the upper 20 km of the crust. Only three intermediate depth earthquakes (85-90 km deep) located in southern

Tibet were reported (see Fig.1) (Chen et al., 1981; Molnar and Chen, 1983; Ekstrom, 1987; Chen, 1988). Due to the lack of seismic stations on the plateau, almost all of above studies used records from stations outside the plateau, usually at teleseismic distances, thus limiting the number of events that could be investigated. However, from 1991 to 1992, a PASSCAL experiment was conducted on the Tibetan Plateau with a deployment of 11 broadband stations. In this report, we present waveform modeling results of 3 events which show strong evidence of subcrustal focal depths. One of the events is located in the same area as two of previous intermediate depth events (Fig. 1), and the other two lie under the Himalayan Thrust Belt (HTB), where, to our knowledge, few intermediate depth events have been reported to date.

Data and Results

The stations occupied during the 1991-1992 Tibet PASSCAL experiment were equipped with STS-2 Streckeisen seismometers which have a flat velocity response between 0.008 to 50 Hz. The details of the instrumen-

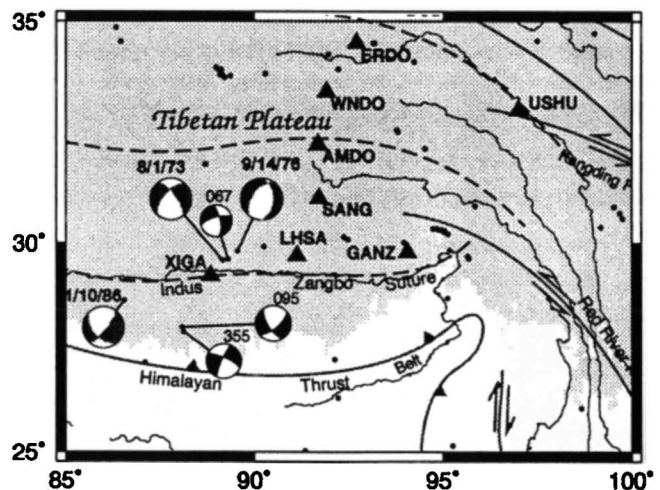


Figure 1. Map of southeastern Tibet showing major tectonic boundaries and the station locations (triangles) of the 1991-1992 Tibet PASSCAL experiment. Shading indicates elevation above 3 km. Darkly shaded focal spheres are for subcrustal events analyzed in this study. Lightly shaded focal spheres are from Molnar and Chen (1983) and the Harvard CMT solution (for event on 1/10/86). All of them are located at intermediate depths.

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Table 1. Locations of the Events From PDE Catalog

Event	Date	Origin time	lat./lon./depth	m_b
355	12-21-91	19 ^h 52 ^m 45.5	27.90N/88.14E/ 57	4.9
067	03-07-92	22 ^h 41 ^m 50.8	29.44N/89.37E/113	4.3
095	04-04-92	17 ^h 43 ^m 20.7	28.15N/87.98E/ 33	4.9

tation can be found in Owens et al. (1993). During its one-year deployment, about 50 earthquakes within the plateau were recorded by the array with good signal-to-noise ratios (Fig. 1). Randall et al. (1995) determined the focal depths and moment-tensors of 38 events in the north-central and southeastern part of the plateau by inverting long-period waveforms ($T > 20s$). Their results agree with previous studies that have indicated shallow seismicity.

The PDE catalog locations and origin times of the three events investigated in this paper are listed in Table 1. Events 355 and 095 are reported as crustal events and event 067 as subcrustal. A distinguishing character of all 3 events recorded on the array is their sharp direct P and S arrivals, even at large distances (Fig. 2). This feature suggests a subcrustal focal depth because the first arrivals beyond 320-350 km for crustal events in this region are head-waves with emergent onsets on broadband displacement records.

To test the sensitivity of waveforms to the focal depth, we have calculated the Green's functions for different source depths from 10 km to 90 km, using a re-

Table 2. 1D Velocity Model of the Tibetan Plateau

layer	Th. (km)	V_p (km/s)	V_s (km/s)
1	4	4.70	2.70
2	60	6.20	3.50
3	—	8.14	4.70

flectivity code developed by Saikia and Burdick (1991). The velocity model consists of two layers over a half space with the Moho at 64 km (Table 2). It is very similar to model M45 (Romanowicz, 1982) which has been proved reasonably good for modeling events on the Tibetan Plateau (Randall et al., 1995). Fig. 3 shows the SH component of the Green's functions at a distance of 350 km for various source depths, along with the observed SH displacements for Events 355 and 095 recorded at the same distances. We focus on the SH displacement first because it is much simpler than P-SV displacement and has less dependence on source orientation. By comparing the waveforms for source depths of 60 km (above the Moho) and 70 km (below the Moho), one can see that the waveform shapes are quite diagnostic; the crustal synthetics predict a gently rising S_n phase whereas subcrustal events produce a sharp onset. Furthermore, the strong crustal phase $S_d + S_mS$ vanishes when the source is below the Moho. From the sharp S arrivals and lack of S_d/S_mS in the

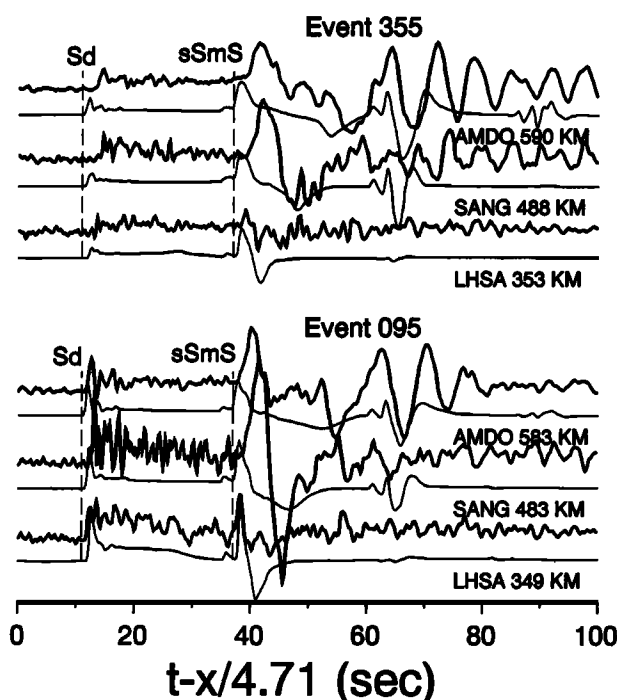


Figure 2. Examples of SH displacements of events 355 and 095 (thickened traces). Note the sharp onsets of S waves. The corresponding synthetics are computed using the 1-D model (Table 2) with source mechanism and depth obtained from waveform inversion.

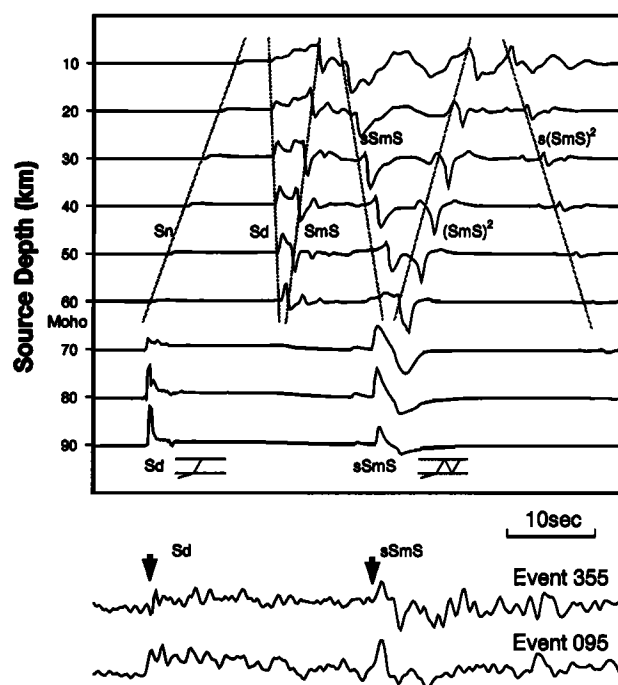


Figure 3. SH components of the Green's functions of a strike-slip source at different depths. The velocity model is given in Table 2. Distance range is 350 km. Also shown in the figure are observed SH displacements of Events 355 and 095 recorded at station LHSA at the same distances.

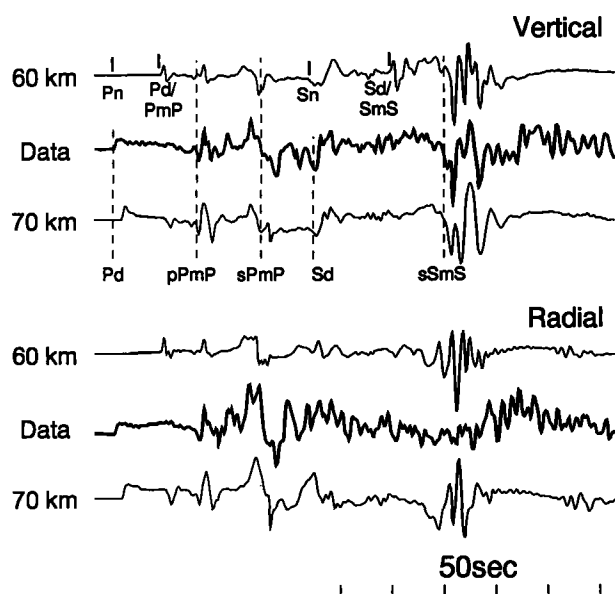


Figure 4. Comparison of vertical and radial displacements at station LHAS with synthetics from sources above (60 km) and below (70 km) the Moho. The synthetics are constructed using the source mechanisms obtained from the waveform inversion at corresponding depths.

observed waveforms, we conclude that Events 355 and 095 are subcrustal events. The synthetics for sources at 70, 80, and 90 km also show that for deeper source, the shape of first arrival is more impulsive. Accordingly, the step-like shape of first S arrivals indicates that the two events are confined to the uppermost mantle.

Fig. 4 shows a comparison of vertical and radial displacements for Event 355 with synthetics generated from a source above the Moho (60 km) and below it (70 km). Source mechanisms obtained from inversion of the whole array data are used when constructing the synthetics. Although the long period features of data and the two corresponding synthetics are similar, as is expected from theoretical arguments (Helmberger and Malone, 1975), the synthetics for subcrustal focal depths match the broadband features of the data much better, with many individual phases aligned.

To invert whole broadband seismograms for source depths and mechanisms, we apply a grid search in the source parameter space (strike, dip, rake, M_0 , depth) to find the global minimum of misfit between the synthetic and observed waveforms (Zhao and Helmberger, 1994). An advantage of the method is that it allows time shifts between various portions of the observations and synthetics, thus relaxing the strong dependence of the inversion on the velocity model and the influence of lateral variation. Uncertainty of the solution can be estimated easily by quantifying the misfit error distribution around the global minimum.

The global minima of the 3 events as a function of depth are shown in Fig. 5. As expected, the waveform misfit errors of all 3 events decrease rapidly as the

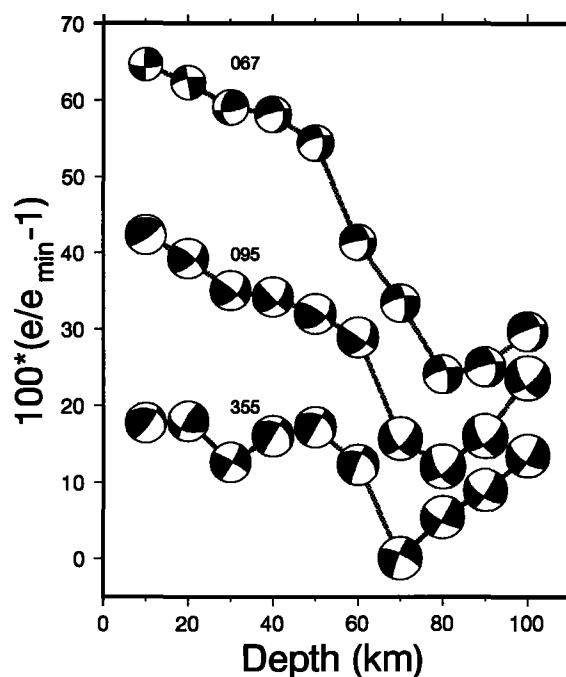


Figure 5. Waveform misfit as function of focal depth. The misfit errors are normalized by the minimum. Curves for Event 095 and 067 are offset for displaying reason.

sources drop below the Moho. The mechanisms show some depth dependence but remain mostly strike-slip. Table 3 lists the inversion results at the best-fit depths and the uncertainties estimated by examining all the solutions with misfit errors within 5% of the minimum. For all 3 events, the azimuths of the P and T axes are better constrained (within 10°), while the plunges are relatively poorly constrained (within $10^\circ - 20^\circ$).

In Fig. 1 we have plotted the lower-hemisphere projection of the best fault plane solutions. The source mechanisms of the two events under the HTB display strong strike-slip behavior with some normal faulting. They are quite different from the mechanisms of shallow events in the same area, which show consistent low-angle thrusting along the front of the Himalaya with slip vectors perpendicular to the mountain range (Molnar and Chen, 1983; Baranowski et al., 1984; Ni and Barazangi, 1984; Molnar and Lyon-Caen, 1989). The mechanism of the event near the suture zone is similar to the mechanism of the previous intermediate depth event nearby (Fig. 1), except that it has more strike-slip component. The T-axes are all horizontal in the

Table 3. Focal Depths and Fault Plane Solutions From Waveform Modeling

Event	P axis ^a	T axis ^a	<i>h</i> (km)	M_0
355	157±6/ 6±20	252±7/3±15	70	1.41
067	210±6/27±11	303±8/3±11	80	0.25
095	6±6/31±11	277±9/3±14	80	2.00

^aAzimuth/Plunge, all in degrees; M_0 in 10^{16} Nm.

EW direction and the P-axes are roughly in the NS direction. This is consistent with a regional stress field produced by the indenting of the India continent.

Discussion

Focal depth determinations based on global network traveltimes have always been difficult because of the trade-off between the depth and origin time (Zhao and Helmberger, 1991). This trade-off can be eliminated by the use of depth phases, pP and sP, but these phases become difficult to identify for magnitudes below 5, especially for strike-slip orientations. With broadband records at regional distances, the constraints on focal depths can be substantially improved. In particular, waveform modeling proves very effective in discriminating between crustal and subcrustal events, due to their fundamental waveform differences. Moreover, our success in modeling the broadband waveforms up to 1000 km distance range with a simple 1D velocity model shows that to the first order the plateau has a relatively simple crustal structure. But we also emphasize that lateral variation does exist. For example, the tangential displacements at stations WNDO, ERDO, and BUDO are delayed about 5 sec relative to the synthetics. These three stations are located in the north-central plateau where a mid-crustal low velocity zone is reported (Brandon and Romanowicz, 1986; Zhu et. al, 1995).

In summary, we have detected 3 intermediate depth earthquakes in the India-Tibet collision zone in a one-year time window. Taking into account three previous reports, it is reasonable to speculate that there are other unidentified intermediate depth earthquakes with moderate magnitudes in this area. The existence of intermediate depth earthquakes under the Himalaya and Indus Zangbo suture indicates the temperatures of the mantle lithosphere in southern Tibet are relatively low. The small number of these events studied to date limits our ability to explore the details of structure and rheology of the lithospheric mantle, but we believe that with the installation and operation of the permanent CDSN station at Lhasa, more data will be available to shed light on questions about the tectonics in this continent-continent collision zone.

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